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Water Management Adaptation with Climate Change

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Publication Date
2009-08-01

WATER MANAGEMENT ADAPTATION WITH CLIMATE CHANGE

A Paper From:
California Climate Change Center

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FINAL PAPER

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Arnold Schwarzenegger, *Governor*

August 2009
CEC-500-2009-049-F

Acknowledgments

The authors are thankful to Stacy K. Tanaka (Watercourse, Inc.), Marion W. Jenkins (University of California, Davis), Julien J. Harou (University College of London), and Tingju Zhu (International Food Policy Research Institute) for their valuable inputs and research support. Support from the Public Interest Energy Research (PIER) program is appreciated.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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- Energy-Related Environmental Research
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- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

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For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

This paper explores water management adaptation in California to warm-dry and warm-only climate warming scenarios from the updated scenarios for the California Climate Change Scenarios Assessment 2008. CALVIN, an optimization model of California's intertied water supply system, is employed to explore adaptation strategies for year 2050. EBHOM, an optimization model of high-elevation hydropower systems in California, is used to estimate adaptation in energy generation. A historical (1921–1993) hydrology is used as a reference. The warm-dry scenario is developed using permutation ratios for a 30-year downscaled simulation (from the Geophysical Fluid Dynamics Laboratory's CM2.1 model using the Special Report on Emissions Scenarios A2 scenario) centered at 2085. The warm-only scenario was developed based on the warm-dry hydrology, preserving the early snowmelt from the warm-dry scenario while maintaining the mean annual flows of the historical hydrology. This will aid separation of precipitation and temperature effects for adaptation to climate change. Agricultural and urban water uses for the year 2050 are obtained from two ancillary models. Results predict significant adaptation to warm-dry and warm-only climates. Water scarcity occurs from the drier climate in the warm-dry scenario, with increasing competition among water uses. Early snowmelt and peak storage characterize warmer climate scenarios in California. Warm-only scenario scarcity costs are significantly less than for the warm-dry scenario.

Keywords: Climate change, adaptation, water management, optimization, water demand

1.0 Introduction

Global climate warming has inspired volumes of literature which explore the potential effects of various climate scenarios on water management. California has taken a proactive role in assessing climate change impacts for public health, water resources, agriculture, forests and landscape, and rising sea levels (Franco et al. 2008). This paper provides a quantitative exploration of adaptation on water resources management for California for two climate scenarios: warm-dry and warm-only global warming. The warm-dry scenario is based on a downscaled Geophysical Fluid Dynamics Laboratory (GFDL) CM2.1 model A2 scenario climate simulation centered in the year 2085 following the methods in Medellín-Azuara et al. (2008). This warm-dry scenario yields a statewide-average 4.5°C (8.1°F) rise and an 18% reduction in precipitation by the end of the century (Cayan et al. 2008). A warm-only hydrology based on the GFDL CM2.1 A2 simulation was developed to retain the same pattern of early snowmelt and low rim flows in the summer, but with the historical (1921–1993) mean annual runoff.

The CALifornia Value Integrated Network (CALVIN, Draper et al. 2003) model, a large-scale economic-engineering optimization model of California's integrated water supply system, is used for this study. Previous work with CALVIN includes exploring water management adaptations toward 2100, considering population growth and climate warming (Tanaka et al. 2006) and a warm-dry climate towards year 2050 (Medellín-Azuara et al. 2008). This study assesses the likely effect of average temperature rise under a high-emissions scenario on water allocation and hydropower generation.

2.0 Methods and Model Overview

CALVIN is an economic-engineering optimization model for the intertied network of water resources in California (Draper et al. 2003). Recently, the model has been expanded to include northern Baja California, Mexico (Medellín-Azuara et al. 2007b). CALVIN includes major conveyance and water treatment infrastructure, extensive surface and groundwater reservoirs, and more than 88% of agricultural and urban demand areas statewide. The network in CALVIN (Figure 1) also includes storage, conveyance, and treatment capacities; minimum instream flow requirements; operating costs; and water scarcity costs from water shortages. Most water demand areas are represented economically with penalty functions for water shortages. When deliveries fail to fulfill target water demands, scarcity costs or penalties reflect that shortage.

The model then allocates water for uses with higher scarcity costs and lower operating costs within represented policies regarding water allocation, groundwater pumping, surface reservoir storage and release, and minimum instream and environmental water flows. The CALVIN database is frequently updated to include new infrastructure and to improve representation of agricultural, urban, and environmental water uses statewide.

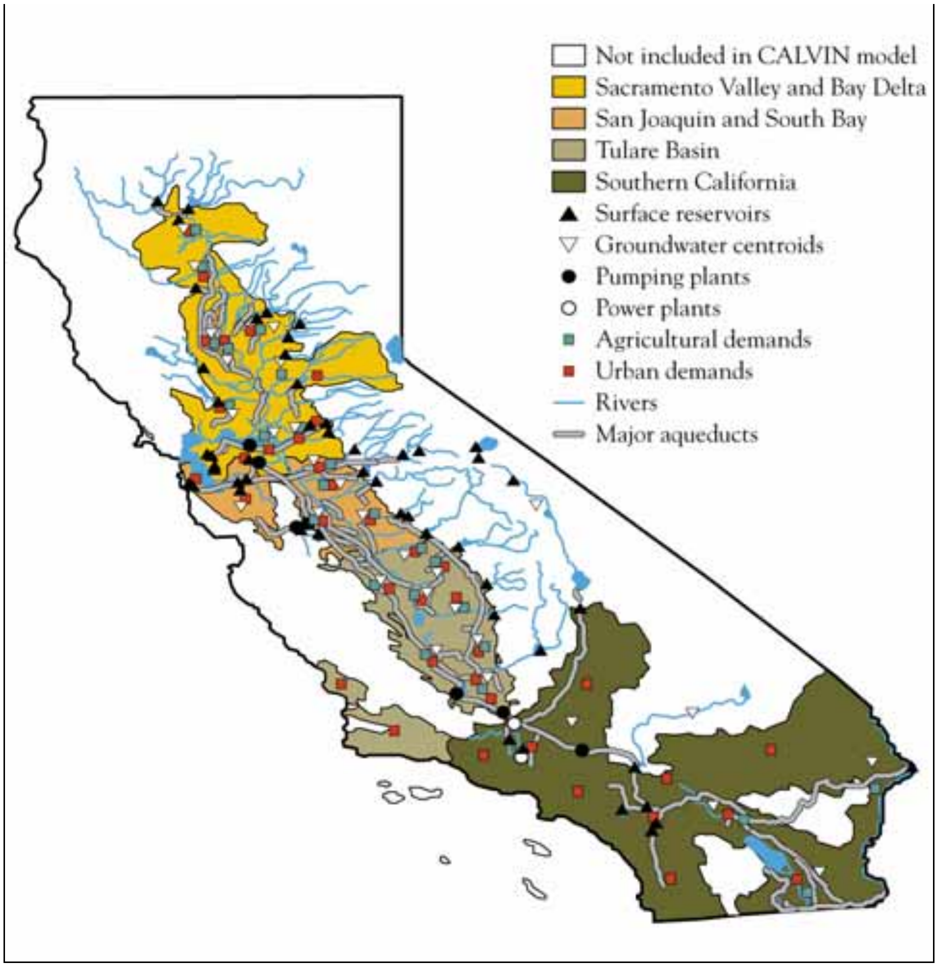


Figure 1. California's statewide water supply network, represented in CALVIN (after Lund et al. 2007)

2.1. Agricultural and Urban Water Demands

Shortage penalties for agricultural and urban uses come from two ancillary models: the Statewide Agricultural Production Model (or SWAP, after Howitt et al. 2001) for agricultural water use; and a urban shortage losses model described in Jenkins et al. (2007).

Urban and agricultural water demands are related to projected changes in land use. As shown in Table 1, urban land use between 2020 and 2050 is expected to increase statewide by 35%, with agricultural land use reductions of 5.1%.

Estimations for water demands follow previous CALVIN applications for the year 2050 (Jenkins et al. 2007; Medellín-Azuara et al. 2008, 2007a).

Table 2 compares the changes in projected agricultural and urban water demands between years 2020 and 2050, indicating total target demands system-wide of 37.5 million acre feet per year (MAF / yr) (46.2 billion cubic meters per year, or BCM / yr).

Table 1. Expected changes in land area between 2020 and 2050 (adapted from Landis and Reilly 2002), and CALVIN-SWAP region crop areas

	Urbanized Land			Agricultural Land*		
	Regional Total Area, Acre (ha)		% Change	CALVIN Regional Total Area, Acre (ha)		% Change
	2020	2050		2020	2050	
Northern California and Sacramento	1,337,465 (540,737)	1,663,876 (660,576)	22.2	1,713,900 (693,590)	1,656,771 (670,495)	-3.3
San Joaquin Valley and Tulare	646,381 (261,587)	1,044,333 (422,224)	61.4	5,083,100 (2,057,057)	4,797,749 (1,941,649)	-5.6
Southern California	2,550,040 (1,030,981)	3,442,696 (1,391,882)	35.0	964,360 (390,262)	905,394 (366,413)	-6.1
Statewide	4,534,516 (1,833,305)	6,120,905 (2,474,682)	35.0	7,761,360 (3,140,911)	7,363,711 (2,980,094)	-5.1

*Note: For agriculture, Northern California includes Central Valley Production Model (CVPM) regions 1 to 7. The San Joaquin Valley and Tulare represents CVPM regions 8 to 21. Southern California considers projections of Landis and Reilly (2002) for agricultural areas in the counties that include Coachella, Imperial Valley, Palo Verde, and the counties of Ventura and San Diego.

Table 2. CALVIN agricultural and urban target water demands for years 2020 and 2050
(from Medellín-Azuara et al. 2008 and new estimates)

	Urban TAF/year (BCM/yr)			Agricultural TAF/year (BCM/yr)		
Region	2020	2050	% Change	2020	2050	% Change
Sacramento Valley	1,904 (2.3)	1,887 (2.3)	-0.9%	9,005 (11.1)	7,863 (9.7)	-12.7%
San Joaquin Valley	1,535 (1.9)	1,816 (2.2)	18.4%	5,259 (6.5)	4,052 (5.0)	-23.0%
Tulare Basin	1,199 (1.5)	1,535 (1.9)	28.0%	9,773 (12.1)	8,871 (10.9)	-9.2%
S. California	7,426 (9.2)	8,107 (10.0)	9.2%	3,716 (4.6)	3,336 (4.1)	-10.2%
Total	11,740 (14.5)	13,346 (16.5)	10.6%	27,753 (34.2)	24,123 (29.8)	-13.1%

Note: TAF = thousand acre feet; BCM = billion cubic meters. Grouping may differ slightly from the previous table. Agricultural water demands in Southern California do not include San Diego and Ventura counties.

2.1.1. Agricultural Water Demand

The SWAP model provides the CALVIN model with derived water demand functions for 24 agricultural areas including 21 regions of the Central Valley Production Model (CVPM after Hatchett 1997) plus Coachella, Imperial, and Palo Verde irrigation districts in Southern California.

Previous applications of SWAP to climate change (Medellín-Azuara et al. 2007a) had acreage mostly based in the U.S. Department of Agriculture (USDA) agricultural commissioner's report. Previous water use estimations in agriculture are described in the appendixes of Jenkins et al. (2001). These take into account the relationship between applied water and evapotranspiration for all SWAP regions in an *average year*. For this study water use follows both previous estimates and newer ones using DWR applied water use reports per crop group.

Innovations with respect to previous studies with SWAP (e.g., Howitt et al. 2001; Medellín-Azuara et al. 2007a) are described in Howitt et al. (2008). Among them, geo-referenced data on land use from the California Department of Water Resources (DWR) are combined with county agricultural commissioners' reports from the USDA to obtain a more precise pattern of land and water use. Average cost information for land rental cost per crop and region, water, labor, and an amalgam of supplies for agricultural production is used. Through positive mathematical programming (Howitt 1995), agricultural production functions per crop and region for a representative producer are obtained. These functions are self-calibrated to land use then following Howitt (1995).

The current database in SWAP (see Howitt et al. 2008) includes data from land use surveys done by DWR for existing regions, plus agriculture in Ventura and northern San Diego County (Figure 2). These last two regions are being incorporated into CALVIN, and according to DWR 2005 reports they have a current estimated demand of 221 TAF/yr (273 million cubic meters, or MCM) and 214 TAF/yr (264 MCM) respectively; however their combined demand is expected to drop down to 350 TAF/yr (431 MCM) by mid-century, mostly due to urbanization.

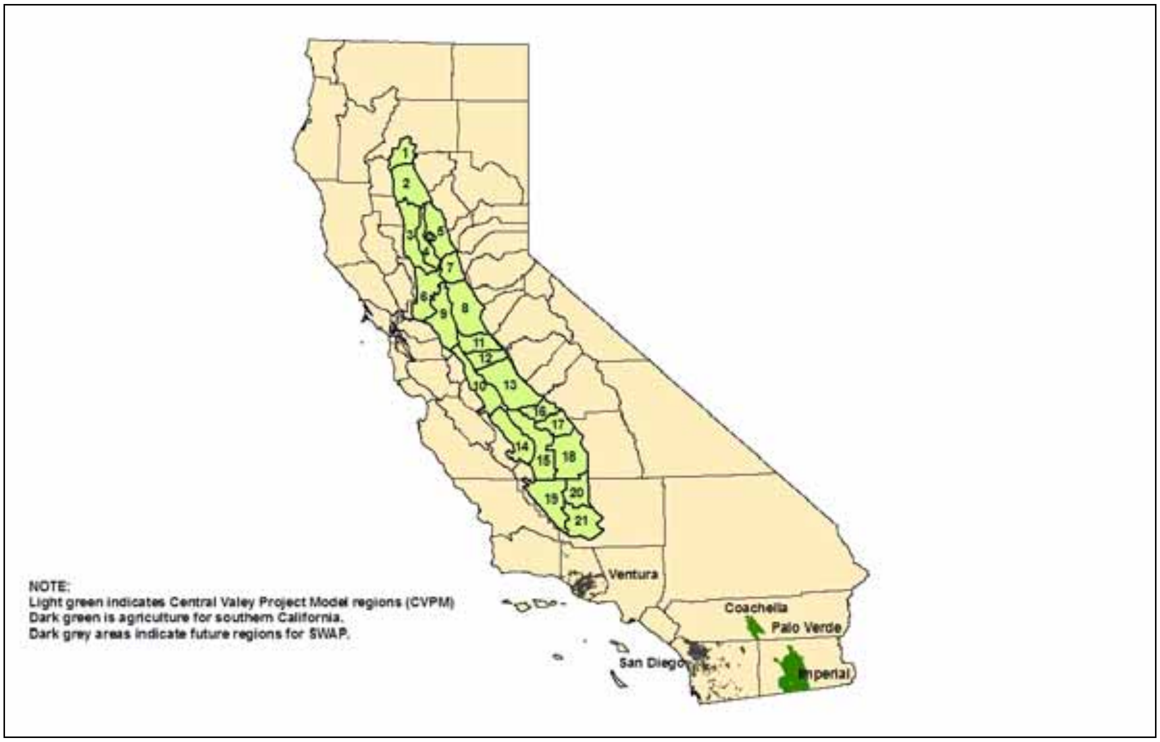
Table 3 details previous and newer agricultural water use projections in SWAP per region by 2050. The CVPM regions 1 thru 4 (Figure 2) in Northern California are not part of the Landis and Reilly (2002) study and are assumed to maintain current agricultural land use. Other changes in agricultural land use in agriculture to SWAP and CALVIN are detailed in Jenkins et al. (2007).

Table 3. Comparison of agricultural water demand in previous CALVIN studies

	Study		
CALVIN Region	**CALVIN (2001) Projected 2020 in TAF/yr (BCM/yr)**	**CALVIN (2005) Projected 2050 in TAF/yr (BCM/yr)**	**CALVIN (2008) Projected 2050 in TAF/yr (BCM/yr)**
Sacramento	9,005 (11,108)	9,262 (11,425)	7,863 (9.7)
San Joaquin	5,259 (6,487)	6,344 (7,825)	4,052 (5.0)
Tulare	9,773 (12,055)	10,399 (12,827)	8,871 (10.9)
Southern California	3,716 (4,584)	3,271 (4,035)	3,336 (4.1)
Total	***27,753 (34,233)***	***29,276 (36,112)***	***24,123 (29.8)***

Comparing the CALVIN 2005 Climate study (Medellín-Azuara et al. 2008) with the present one, differences in water use projections by 2050 are related to improved distribution of crop acreages within CVPM regions due to the use of georeferenced information at a parcel level.

A calibrated production function can be later used to simulate policies such as water shortages, exogenous shocks and other changes in parameters. Four of these changes are incorporated into SWAP for this study for 2050. The first is a reduction in agricultural land use following Landis and Reilly (2002). The second is an increase in yields due to technological advancement using estimations by Brunke et al.(2004) for year 2030 but capped to 28.8% by 2050. A third shift in the demand for crops in California by 2050 is related to the income projections and the expected proportion of California exports. And fourth, yield changes due to climate warming under a warm-dry high-emissions scenario (GFDL CM1 A2), by Lobell and Field (2008), Lee et al. (2008) and previous ones from Lobell et al. (2007) and Adams et al. (2003).



NOTE:
Light green indicates Central Valley Project Model regions (CVPM)
Dark green is agriculture for southern California.
Dark grey areas indicate future regions for SWAP.

Figure 2. Coverage of the Statewide Agricultural Production Model (SWAP)

A derived water demand function per region is obtained by reducing water availability (after the four shifts described above), and capturing the marginal value on the water constraint for the region. A water-derived demand function is later integrated to estimate the cost of water shortage for agriculture in a region. The derived demand functions per region are integrated numerically to obtain economic cost of shortages (or penalties for shortage) for CALVIN. For this CALVIN study, the value average product of water was used *in lieu* of the marginal value on the water constraint. This approach increases economic costs of shortages for agriculture to values closer to observed water market transactions.

Water requirement estimations in SWAP based on land use are slightly different at the level of CVPM regions compared to previous CALVIN studies (Medellín-Azuara et al. 2007a). Although this calibration process for SWAP is still ongoing, results indicate some CVPM regions in the northern Central Valley use less water than previously estimated. For the agricultural areas covered by SWAP and CALVIN, the overall trend is a reduction in agricultural water use from 2020 to 2050 of roughly 3.630 MAF/yr (4.45 BCM/yr), a 13.1% decrease (Table 2). Most of this water use reduction occurs in the Central Valley, where the agricultural land reductions are the highest. Differences in previous estimates of agricultural water use (second column of Table 3) are related to updated information on land use projections. Furthermore, projected crop mixes in SWAP for year 2050 are expected to shift toward less water intensive crops. Finally, the Landis and Really (2002) agricultural versus urban land use conversions were applied on a coarser basis, following DWR estimates for the larger hydrological regions of the Sacramento and San Joaquin Valleys and the Tulare Basin, where the 21 CVPM regions are contained.

Crop yield changes significantly affect total agricultural revenues with in a warm-dry climate scenario by 2050. Figure 3 shows a CALVIN penalty function obtained from SWAP, where the cost of scarcity under climate change for agriculture is higher. Howitt et al. (2008) conclude there are significant losses in agricultural revenues under climate change relative to historical climate. However, increasing crop prices may compensate in part for yield losses associated to climate change. For CALVIN, this implies higher cost of shortages for agriculture, thus less agricultural scarcity might be expected as the willingness to pay in farming activities is higher, resulting in higher operating costs to obtain water and less water transfers to urban uses.

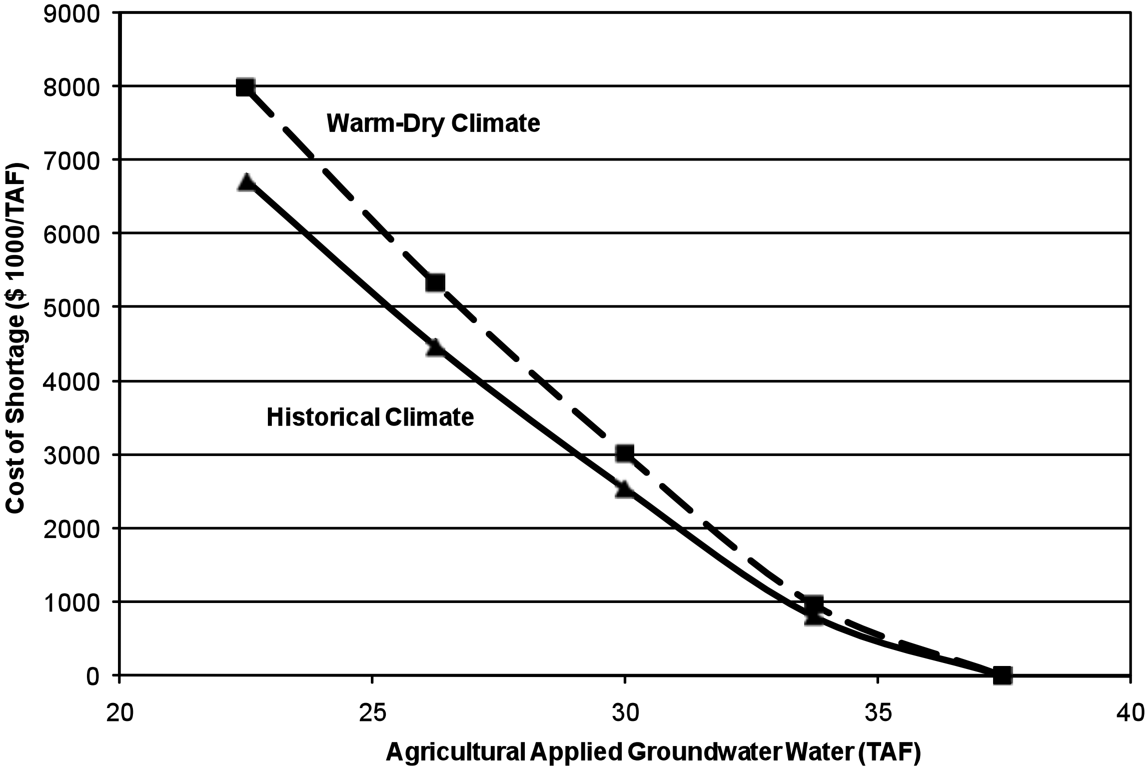


Figure 3. Comparison of agricultural water shortages cost under historical and warm-dry climate for groundwater deliveries in CVPM 7 (Sacramento Basin) in the month of May.

2.1.2. Urban Water Demand

Urban water use penalties follow the methods described in Jenkins et al. (2003) with population growth projections to year 2050. Land conversion from agricultural to urban uses follows Landis and Reilly(2002). Figure 4 shows the ongoing update of population projections for year 2050 as part of the 2008 California Climate Assessment.

Table 2 shows estimated water demand for year 2050 for the urban locations included in CALVIN (Jenkins et al. 2007).

Economic costs of shortages for urban use are obtained from population and economic sector water use. The base 2050 population for the CALVIN model coverage area (Figure 1) is 54 million, representing roughly 82.9% of the projected 2050 California population. This is translated into a total water demand target of 13,346 TAF/yr (16.5 BCM/yr) an 11% increase over projected 2020 water demand. This assumes water conservation and other measures lower per capita consumption from 240 gallons (908 liters, L) to 221 gallons (837 L) per day (Jenkins et al. 2007).

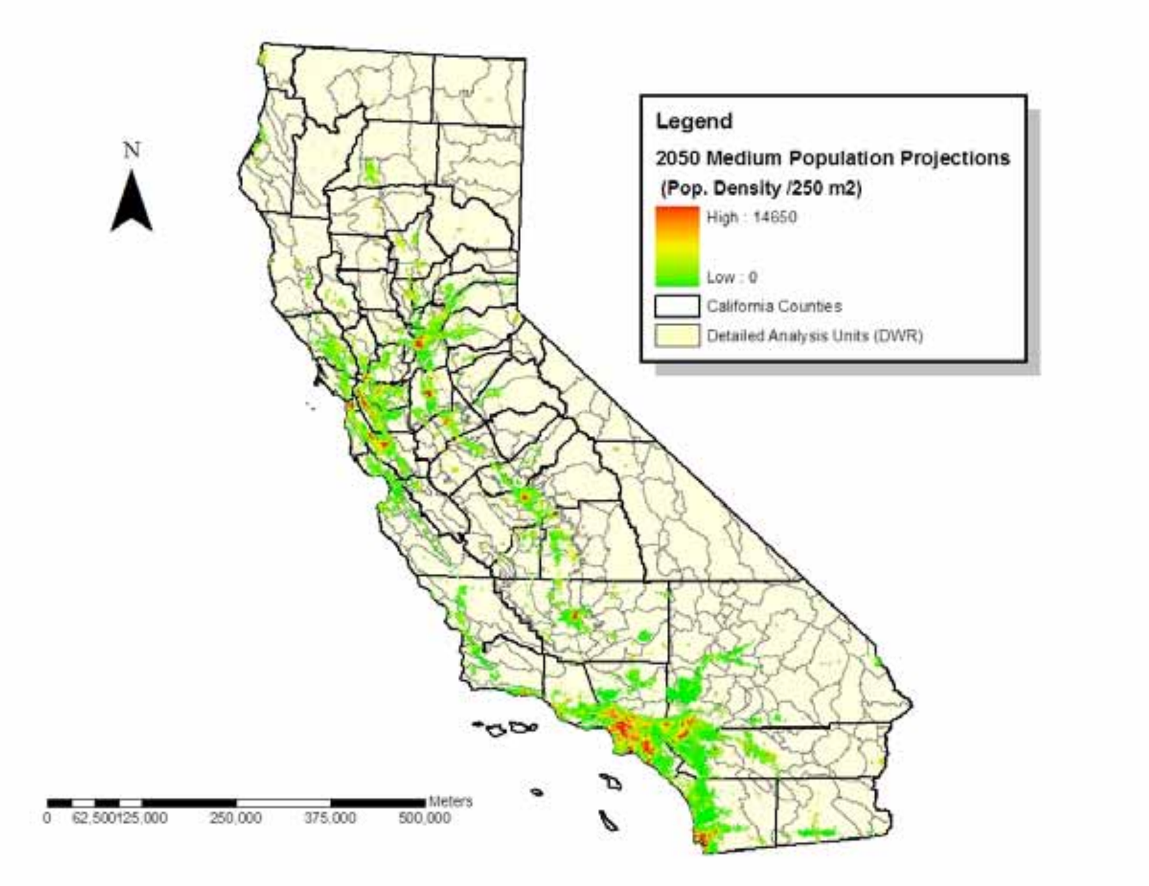


Figure 4. Population projections for year 2050 at middle level of development (Source: 2008 California Climate Change Assessment)

The estimation of shortages for urban uses is an amalgam of residential, commercial, and industrial water uses in California. Residential users are assumed to respond to water price changes, whereas commercial and urban users for whom water consumption represents a rather minor operating or production cost respond less dramatically to water prices with fixed water use for these economic sectors.

2.2. Hydrology

The GFDL CM2.1 model with a scenario of relatively high emissions (the *Special Report on Emissions Scenarios* [SRES] A2 scenario) was selected for this study. Downscaled effects of the scenario were used to estimate temperature and precipitation conditions for a 30-year period centered on 2085. Outputs from the global climate model simulated a warm-dry scenario with 4.5°C (8.1°F) increases in annual temperature by the end of the century (Cayan et al. 2008). A warm-only scenario was also examined with adjusted hydrology based on the perturbed warm-dry and historical hydrology, since the global climate model did not directly simulate a warm-only scenario. The warm-only scenario maintains the average annual streamflow of historical hydrology, but it captures the shift in timing expected from warming temperatures.

Temperature shifts, precipitation changes, and monthly streamflow at 18 index basins were used to perturb CALVIN hydrology following Zhu et al. (2005). Hydrologic processes perturbed for climate change include rim inflows (streamflows entering the boundaries of CALVIN), net evaporation rates at reservoirs, groundwater inflow, and net local accretions. Perturbing time series for these hydrologic processes adjusts the hydrology for each climate change scenario to represent its impact on California’s water supply.

2.2.1. Rim Inflows

Permutation ratios capturing the effects of magnitude and timing shifts in streamflows from 18 index basins were used to perturb CALVIN rim inflows. This method maps the hydrologic changes in index basin streamflows to CALVIN rim inflows producing a new climate change time series for each of 37 rim inflows. This requires each CALVIN inflow to be matched with a representative index basin. In the previous climate change study for the Energy Commission using CALVIN, six index basins with flows for 1950–2099 representing different climate change scenarios were available from downscaled global climate models. These six basins were matched to each of CALVIN’s 37 rim inflows to produce climate-adjusted flows for the model. These six representative basins were: Smith River at Jed Smith State Park, Sacramento River at Delta, Feather River at Oroville Dam, American River at North Fork Dam, Merced River at Pohono Bridge, and Kings River at Pine Flat Dam. For the current study, 18 index basins were available to aide in matching CALVIN rim inflows to appropriate basins.

Matching methods from the previous study were applied and adjusted as needed to select appropriate index basins for each of the CALVIN rim inflows. To improve representation, the water year was divided into wet and dry seasons (October thru March and April thru September, respectively). This break in the year was applied for some of the statistical analysis which included selecting maximum correlation coefficients between CALVIN time series and index basin time series, and identifying the least sum of the squared error of these series. This statistical analysis resulted in a table indicating potential annual or seasonal matches of index basins for each CALVIN inflow. Visual comparison of average monthly time series of these potential index basins and CALVIN flows was then made to help select the best match. Finally, expert judgment considering geographic location and knowledge of hydrological processes of each basin (e.g., rain-dominated, snowmelt runoff) played a definitive role in establishing a match.

Perturbation ratios from each index basin were applied to the corresponding CALVIN flow to shift the time series of flow in time and magnitude. This generates the warm-dry climate adjusted rim inflow times series input to CALVIN. Resulting perturbation ratios for the warm-dry scenario indicate a general decrease in magnitude of flow as well as a shift in timing indicating an earlier snowmelt, as shown for the Sacramento and San Joaquin Rivers in Figure 5.

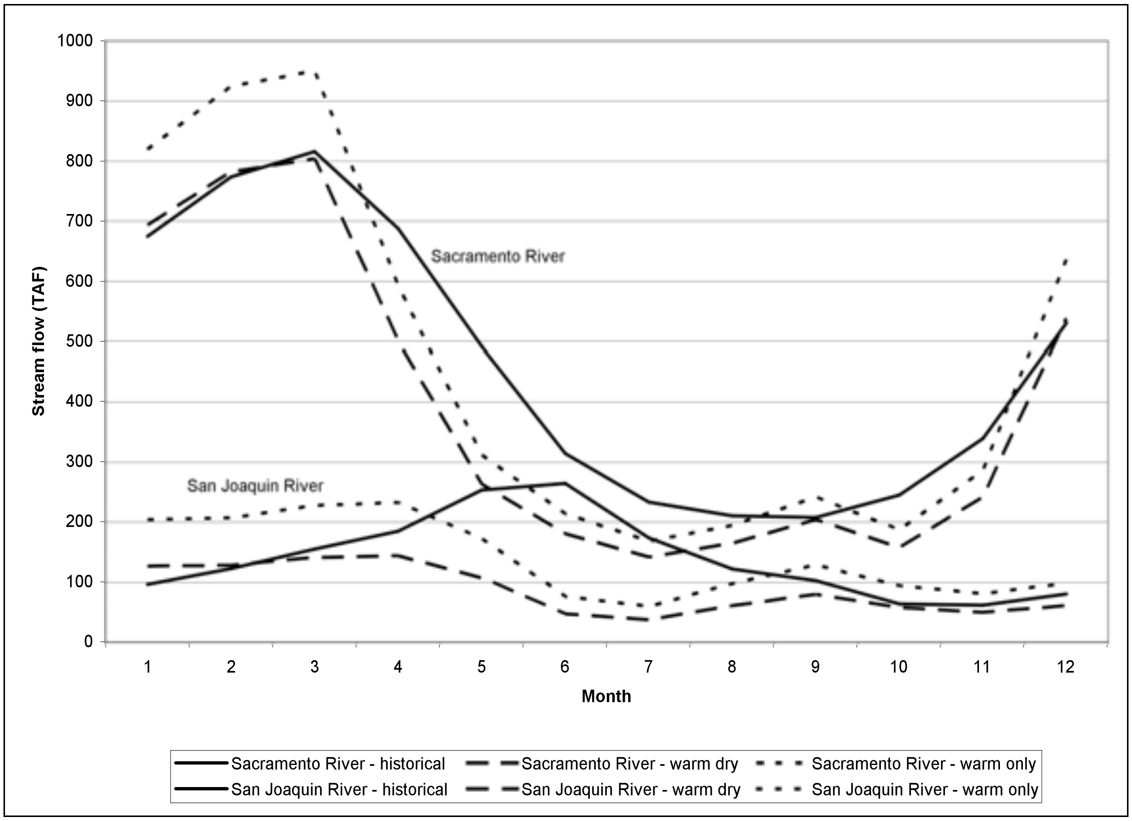


Figure 5. Sacramento River (at Shasta Dam) and San Joaquin River (at Millerton) mean monthly streamflows, 1921–1993, for each modeling scenario

A downscaled global climate model to represent a warm-only hydrology was not available. Therefore, adjusted rim inflow time series from the warm-dry scenario were used to represent this additional scenario. As with the warm-dry series, permutation ratios were applied to the historical time series to capture the effect of warming (shift in hydrograph timing). To reverse the effect of decreased precipitation for the warm-only scenario, the historical time series was multiplied by the ratio of average historical flows to average warm-dry flows. As a result, the warm-only time series mirrors the timing of the warm-dry scenario but with greater magnitudes so that average annual streamflow equals that of the historical scenario (Figure 5). The method is limited by the permutation ratio’s dual representation of warming and reduced precipitation. Since the method assumes a warming and drying effect is present in every time step at every location, the approximation could lead to overcompensation of precipitation adjustments in months where the permutation ratio in fact primarily represents effects of warming. This could lead to overestimation of streamflows during these times.

2.2.2. 18 vs. 6 Index Basins

Six index basins with downscaled climate perturbed streamflows were available for the previous climate change study. The current study used 18 index basins to match index basin streamflows with CALVIN rim inflows. These additional basins include a range of tributaries of the Sacramento and San Joaquin Rivers from the east side of the valley, and the Trinity River in the north, a tributary to the Klamath. Here we present a comparison of rim inflows generated using 6 index basins from the previous study with those generated by mapping with 18 index basins in the current study.

With 18 available index basins, 8 of them were directly mapped to a CALVIN rim flow (e.g., Trinity River mapped to Trinity River). These basins include the Trinity River, Sacramento River at Shasta Dam, Feather River at Oroville, Calaveras River at New Hogan, Consumnes River at McConnell, Stanislaus River at new Melones Dam, San Joaquin River at Millerton, and Kings River at Pine Flat Dam. The only river directly matched in the previous study for wet and dry seasons was the Kings River. On a local scale, the improved mapping can have a significant effect on the annual average streamflow, as in the case of the Feather River (Table 4). Mapping it to the Feather River at Oroville for wet and dry seasons led to a decrease in annual average flow of 170 TAF/yr compared to the climate adjusted flow of the previous study. However, in other cases, as with the Stanislaus, the improved mapping had little effect on the projected climate perturbed streamflow.

Table 4. Perturbed streamflow resulting from mapping using 6 and 18 basins

	18 Index Basins	6 Index Basins		% Change from Historical		Ann. Avg. Difference in TAF/yr (MCM/yr)
CALVIN Rim inflow	**Wet & Dry**	**Wet**	**Dry**	**18 Basin**	**6 Basin**	
Trinity River	Trinity	Sacramento R. at Delta	Sacramento R. at Delta	-15%	-21%	71 (88)
Sacramento River	Sacramento R. at Shasta	Sacramento R. at Delta	Sacramento R. at Delta	-15%	-15%	0
Feather River	Feather R.	Feather R.	Sacramento R. at Delta	-24%	-20%	-170 (-210)
Calaveras River	Calaveras R.	Smith R.	Smith R.	-27%	-12%	-24 (-30)
Cosumnes River	Cosumnes R.	North Fork American R.	Feather R.	-30%	-16%	-53 (-65)
Stanislaus River	Stanislaus R.	Feather R.	Kings R.	-38%	-38%	4 (5)
San Joaquin River	San Joaquin R.	Feather R.	Kings R.	-38%	-41%	53 (65)
Kings River	Kings R.	Kings R.	Kings R.	-47%	-47%	0

When a direct match could not be made, a representative index basin was mapped to the CALVIN inflow (e.g., Cosumnes mapped to Stony Creek). Statistical analysis, geographic location, and knowledge of hydrological processes characterizing each basin was critical for assigning appropriate matches. For example, low-elevation, rain-dominated basins were matched with basins sharing similar characteristics. When possible, general spatial location was considered in the final decision process such that the Smith basin (one of the few rain-dominated index basins at the far northern end of the state which was used widely in the previous study) was replaced instead by the Cosumnes River basin, also a rain-dominated basin closer to most of the CALVIN rim flows.

2.2.3. Other Climate Perturbed Hydrological Processes

In addition to rim flows, climate-adjusted hydrological processes include net reservoir evaporation, groundwater inflows, and net local accretions following the method described in Zhu et al. (2005).

Changes in reservoir evaporation were based on an empirical linear relationship derived between historical monthly average net reservoir evaporation rates and monthly average air temperature and precipitation (Zhu et al. 2005). For this study the main drivers for net evaporation rates are temperature and precipitation. The resulting perturbed reservoir net evaporation time series provides estimates of changed evaporation rates under the warm-dry climate change scenario. For the warm-only scenario, change in precipitation was set to zero and changes in temperature contributed to perturbed net evaporation rates.

Groundwater storage is determined by changes in deep percolation modeled using an empirical cubic relationship between precipitation and recharge derived from the Central Valley Groundwater-Surface Water Model or CVGSM (USBR 1997). Since estimates of deep percolation depend solely on precipitation, the historical time series of groundwater inflow was used for the warm-only scenario. As a result, effects on groundwater recharge of reduced snowpack and earlier melting are not represented in the warm-only scenario; however, timing and magnitude of historical and warm-dry scenario time series of groundwater storage were similar, so this approximation seems appropriate.

Rim inflows enter the Central Valley from the mountain regions outside the major water demand areas, whereas net local accretions enter the valley floor within the major demand areas. Net local accretions combine local accretions and local depletions. Changes in local surface water accretion are affected by changes in deep percolation and precipitation. Therefore, historical time series were used for local accretions and depletions in the warm-only scenario.

3.0 Results and Discussion

3.1. Hydrology Results

Perturbing hydrological processes statewide for warm-dry and warm-only climate scenarios affects the overall water supply available to meet water demands in the Central Valley.

3.1.1. Perturbed Hydrological Processes

The overall magnitude of precipitation and streamflow for the state remains unchanged for the warm-only scenario. Under the warm-dry scenario, precipitation decreases across all 21 groundwater basins by 27%, a total of 3,834 TAF (4.7 BCM), shown in Table 5. This amounts to about 2.3 inches/yr (5.8 centimeters [cm]/yr) less precipitation statewide and in the Sacramento and San Joaquin valleys and 2.4 inches/yr (6.1 cm/yr) less in the Tulare Basin. This loss of precipitation affects rim inflows, net evaporation rates, groundwater inflow, and net local accretions (Table 6).

Table 5. Average annual change in precipitation by volume and change in precipitation per unit area

	Avg. Annual Change, in TAF (BCM)	% Change	Inches/yr (cm/yr)
Statewide	-3834 (-4.7)	-27%	-2.3 (-5.8)
Sacramento Valley	-1871 (-2.3)	-24%	-2.3 (-5.8)
San Joaquin Valley	-638 (-0.8)	-30%	-2.3 (-5.8)
Tulare Basin	-1324 (-1.6)	-33%	-2.4 (-6.1)

Table 6 summarizes the effects of the warm-only and warm-dry climate scenarios on California's water supply. Compared to the historical climate scenario, rim inflows decrease by 28% in a warm-dry climate. Rim flows in the warm-only scenario maintain the same average annual flow as in the historical climate scenario. Net reservoir evaporation rate statewide increases by 37% in a warm-dry climate. This is driven by increasing temperatures and decreased precipitation rates in the last third of the century. For the warm-only scenario, evaporation rates statewide increase 15%. Results suggest that net evaporation is significantly greater in a warmer and drier climate scenario rather than just a warmer scenario. Groundwater inflows decrease moderately with a 10% reduction from historical inflows statewide. Net local accretions (accretions minus depletions) decrease significantly statewide and regionally in the warm-dry scenario, leading to a large loss of available water to the system. Local accretions decrease from the historical scenario and local depletions significantly increase, especially in the San Joaquin Valley.

Table 6. Changes in California's water supply under warm-dry and warm-only climate scenarios (average annual totals).

	Statewide	Sacramento Valley	San Joaquin Valley	Tulare Basin	Southern California
Rim inflows (TAF/yr; MCM/yr)					
Historical	28244 (34824)	19122 (23577)	5741 (7078)	2826 (3485)	554 (684)
Warm-dry	20301 (25031)	14804 (18253)	3546 (4372)	1584 (1953)	367 (453)
% Change	-28%	-23%	-38%	-44%	-34%
Net Reservoir Evaporation (ft/yr; m/yr)					
Historical	5.1 (1.6)	3.7 (1.1)	6.4 (1.9)	6.6 (2.0)	5.3 (1.6)
Warm-dry	7.1 (2)	5.3 (2)	8.7 (3)	8.7 (3)	7.2 (2)
% Change	37%	43%	37%	32%	36%
Warm only	5.9 (1.8)	4.3 (1.3)	6.9 (2.1)	8.1 (2.5)	6.3 (1.9)
% Change	15%	17%	9%	23%	19%
Groundwater Inflows (TAF/yr; MCM/yr)					
Historical	6780 (8359)	2229 (2748)	1171 (1444)	3380 (4168)	---
Warm-dry	6103 (7525)	1920 (2368)	1035 (1277)	3147 (3880)	---
% Change	-10%	-14%	-12%	-7%	---
Local Accretion (TAF/yr; MCM/yr)					
Historical	4419 (5449)	3549 (4377)	468 (577)	401 (495)	---
Warm-dry	3092 (3812)	2617 (3226)	272 (336)	203 (250)	---
% Change	-30%	-26%	-42%	-49%	---
Local Depletions (TAF/yr; MCM/yr)					
Historic	1448 (1786)	510 (629)	54 (66)	884 (1090)	---
Warm-dry	3217 (3966)	1111 (1370)	359 (442)	1747 (2154)	---
% Change	122%	118%	566%	98%	---

3.1.2. 18 vs. 6 Index Basins

The overall effect of increasing the number of index basins used to perturb rim inflows from 6 to 18 does not lead to a large difference in estimated streamflows entering the Central Valley under this warm-dry climate scenario. Regionally, change to the system is virtually the same using 6 or 18 index basins (Table 7).

However, additional basins do allow better representation of individual annual streamflows. For example, the addition of the Cosumnes River index basin improved representation of several relatively small east side streams. For example, Cache Creek was previously matched to the Smith River for both wet and dry seasons. Examining the hydrograph, Cosumnes River better represents Cache Creek (Figure 6). This is similar for other CALVIN rim flows, including Dry Creek, Stony Creek, and Cottonwood Creek.

Although additional basins improve representation of individual streams, on a regional and statewide scale this does not greatly affect the estimates of overall climate warming impacts on California's water supply. Table 7 shows the percent change in average annual inflow statewide and for each region with respect to historical rim inflows for each of these methods. Overall, using the newly available 18 index basins compared to the original 6 does not significantly change the percent change in inflows. With sufficient downstream storage, differences in the seasonal distribution of flows can be mostly accommodated.

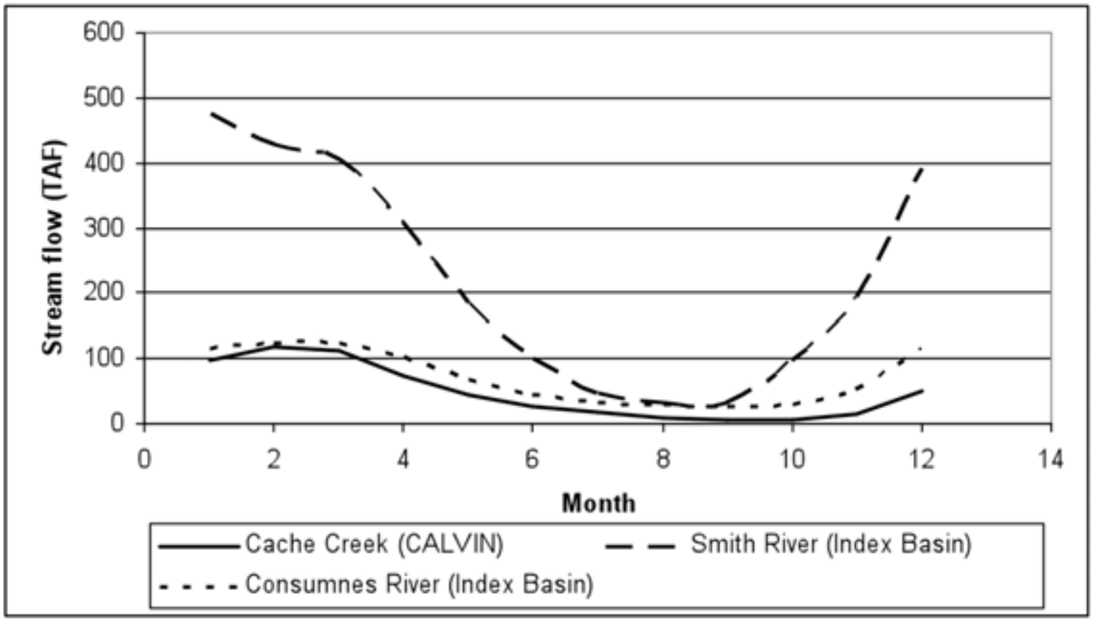


Figure 6. Comparison of Cache Creek to Smith River and Cosumnes River

Table 7. Average annual warm-dry rim inflows, TAF/yr (BCM/yr) for 6- and 18-index basins

	Statewide		**Sacramento Valley**		**San Joaquin Valley**		**Tulare Basin**		**S. California**	
Historical Inflow	28243		19121		5740		2826		554	
Number of Index Basins	18	6	18	6	18	6	18	6	18	6
Climate Perturbed Inflow	20300 (25.04)	20913 (25.80)	14803 (18.26)	15352 (18.94)	3546 (4.37)	3603 (4.44)	1583 (1.95)	1622 (2.00)	367 (.45)	335 (.41)
% Change from Historical	-28.1	-26.0	-22.6	-19.7	-38.2	-37.2	-44.0	-42.6	-33.8	-39.6

3.2. Water Supply Results

Water scarcity patterns under optimized operations for this preliminary study follow those in previous CALVIN studies (Draper et al. 2003; Medellín-Azuara et al. 2008; Tanaka et al. 2006). Agricultural water uses are the most prone to water scarcity for the three hydrologic scenarios. However, these shortages are more likely in Southern California. Very few instances of water scarcity in urban locations are expected since urban willingness to pay for water is much higher than for agriculture.

Table 8 below shows values of water scarcity, scarcity costs, and willingness to pay for additional water for the three climate scenarios statewide. Overall, urban uses are supplied at their target demand (Table 8, fifth column). Small shortages close to 32 TAF/yr (38 MCM/yr) are most likely in Southern California in both historical and warm-only climate scenarios. Affected urban centers (not shown) are some parts of the Metropolitan Water District of Los Angeles and some cities east of Los Angeles within the Mojave and Imperial Valley regions. This conclusion assumes that current infrastructure development projects will be in operation. The dry scenario almost triples shortages for urban locations to 90 TAF/yr (111 MCM/yr). The highest willingness to pay for additional water occurs for cities east of the Los Angeles metropolitan area. This cost can be as high as $358 per acre-ft ($533.4/TCM), as shown in Table 8. In a warm-only scenario, the same mean annual streamflows are preserved; therefore water shortages for agriculture are expected to be in between the ones for historical and warm-dry scenarios. A warm-only scenario has higher evaporation rates than the historical one and a seasonal shift in the hydrograph of the rim flows.

Agriculture suffers the most water scarcity under the warm-dry scenario. Less than 80% of the target deliveries (last column Table 8) are achieved due to the higher opportunity cost of urban scarcity. Water transfers from agriculture to urban uses support the 2050 population and counteract the effects of reduced rim flows, increased evaporation, and other potentially affected elements of the water cycle. This assumes that transaction costs of these changes are small and that the institutional infrastructure exists to support such water transfers (Pulido-Velazquez et al. 2004). Under less severe climate scenarios such as the historical or the warm-only, agricultural water shortages seem to merely support population growth. Thus we conclude that water scarcity is more sensitive to changes in precipitation than to changes in temperature. However, this conclusion has to be tested when a downscaled hydrology of a warm-only scenario becomes available.

Optimized surface reservoir operations (Figure 7) mimic rim flows in Figure 5. Storage peaks about a month earlier for the warm climate scenarios, presumably due to earlier snowmelt. This observation is more evident for the warm-dry scenario. Furthermore, lower levels of storage are to be expected in the summer for the warmer scenarios. Between warm climate scenarios the difference in storage is the largest in the spring, when storage is higher for the warm-only scenario. In the fall, however, monthly average storage is slightly higher for the warm-dry scenario, suggesting that the bias in the methodology may change seasonally. This confirms previous findings regarding surface storage operations (Medellín-Azuara et al. 2008).

Table 8. Water scarcity, scarcity cost, willingness to pay and percent of water deliveries by 2050 (in 2008$).

Scenario	Willingness to Pay ($/AF)	Scarcity Cost ($K/yr)	Scarcity, in TAF/yr (MCM/yr)	Delivery (% of Target)
Historical				
Agriculture	232	200,894	869 (1,072)	96.4
Urban	381	31,091	31 (38)	99.8
Total		231,985	900 (1,110)	
Warm-Only				
Agriculture	232	206,843	893 (1,102)	96.3
Urban	381	32,405	32 (40)	99.7
Total		239,249	925 (1,142)	
Warm-Dry				
Agriculture	251	808,119	5,074 (6,259)	78.9
Urban	658	62,822	90 (111)	99.3
Total		870,941	5,164 (6,370)	

With respect to the historical climate scenario, statewide water scarcity increases by 2.7% with a warm-only climate. In a warm-dry scenario this increase in scarcity is close to 473% (Table 8). Clearly, while climate warming does decrease water deliveries and increase water scarcity, reductions in precipitation, when combined with climate warming, have far more costly effects. The increases in water scarcity costs are similar, 30.1% greater for warming only and 275% greater for the warmer-drier climate. The relatively small additional scarcity created from the warm-only climate arises from the ability of large storage reservoirs, especially when operated conjunctively with groundwater, to effectively adapt to the seasonal shift of runoff (Figure 7). This is in line with classical reservoir operations theory (Hazen 1914), that a reservoir with overyear storage capability will be affected much less by seasonal changes in flows. Most large reservoirs in California have both seasonal and overyear (drought) storage.

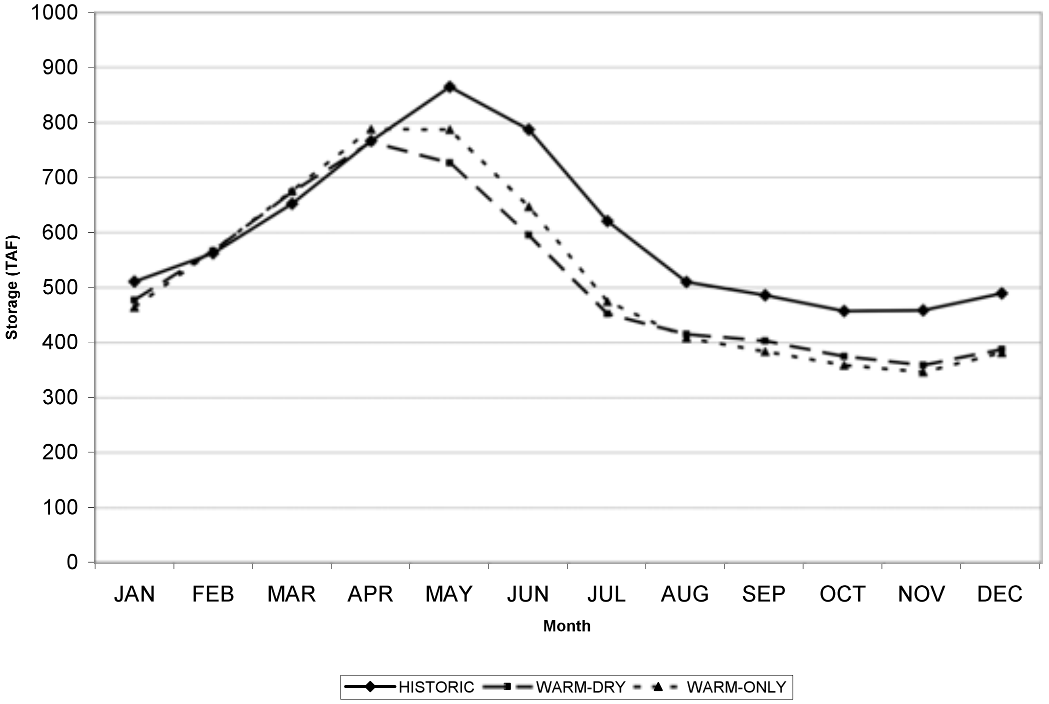


Figure 7. Average monthly storage in New Bullards Bar reservoir

3.3. Environmental Requirements and Model Calibration

Reduced supplies of water under the warm-dry climate came at a cost for some environmental flows. High perturbation ratios for precipitation and temperature by the last quarter of the century translate into abrupt reductions and deep percolation and ultimately, increased losses to the system. A high change in precipitation near Visalia (in CALVIN groundwater basin 18) caused a great reduction in the local accretion for the area compared to the historical climate. This change accounted for nearly 86 TAF/yr (106 MCM/yr) of water losses to accretion unavailable in the system.

Furthermore, reductions in environmental flow requirements for the Trinity River, Clear Creek and the Sacramento River, the San Joaquin/Mendota refuges, and Pixley were required to achieve model feasibility under this dry scenario. A reduction of 8 TAF/yr, roughly 11 % of the average annual minimum streamflow requirement, was applied to Mono Lake water releases from Grant Lake. Changes in end-of-period storage policies in selected reservoirs (such as Shasta) were also needed to accommodate reductions in required minimum streamflows.

Reductions in minimum streamflows, reservoir operation policies, and net local accretions from basin 18 averaged 141 TAF/year (174 MCM/yr) over the 72-year time period. This figure compares with previous infeasibilities under the PCM2100 climate scenario of 329 TAF/year (406 MCM/yr) (Tanaka et al. 2006). Opportunity cost of minimum streamflows can be as high as $1373/AF ($1114 /TCM) in the case of Mono Lake.

3.4. Operating Costs and Hydropower

As a cost-minimizing model, CALVIN helps elicit least-cost water management alternatives to adapt to climate change in California. Table 9 shows a breakdown of changes in operating costs and hydropower benefits for this study's three climate scenarios. Estimations shown in Table 9 do not include costs such as increasing water treatment costs or the transaction cost of switching supplies.

3.4.1. Operating Costs and Benefits from Low-Elevation Hydropower

A warm-dry climate increases total average annual operating costs up to 4.52% ($264.6 million / yr) with respect to historical climate patterns for non-dry years. During dry years, the dry climate scenario can increase operating costs by nearly 1.5% ($92.61million / yr). Lessened rim flows and stored water and increasing evaporation losses force the system to use more costly water supplies. No significant changes in operating costs are expected if precipitation follows historical patterns. Operating costs are upped by $17.6 million in an average year under the warm-only climate scenario (Table 9, second column).

Table 9. Operating costs and hydropower benefits (in 2008$)

		Average Year	
	Historical	**Warm-Only**	**Warm-Dry**
Operating Costs (M$/yr)	5,870	5,887	6,134
(% change from Historical)		0.30%	4.52%
Hydropower Benefits (M$/yr)	445	437	425
(% change from Historical)		-1.9%	-4.50%
		Dry Year	
	Historic	**Warm-Only**	**Warm-Dry**
Operating Costs (M$/yr)	6,140	6,127	6,233
(% change from Historical)		-0.22%	1.5%
Hydropower Benefits (M$/yr)	415	407	388
(% change from Historical)		-1.8%	-6.24%

Benefits from low-elevation hydropower generations are virtually unchanged. These operations are concentrated in Southern California, where patterns of pumping and reservoir water releases are expected to continue at full generation capacity. Nevertheless, these figures do not consider some additional hydropower facilities that are being included in CALVIN. Economic benefits of low-hydropower generation in the lower Sacramento Basin are slightly higher under the dry-climate scenario. This compensates small losses in low-elevation hydropower generation elsewhere in the system.

3.4.2. High-Elevation Hydropower (EBHOM)

Climate warming is expected to shift the runoff peak from spring to winter in California as a result of the reduction in snowpack. The high-elevation hydropower system in California, composed of more than 150 power plants with relatively small reservoirs associated with them, supplies roughly 74% of in-state hydropower supply (Madani and Lund 2008). Such low-capacity reservoir systems have been designed to take advantage of snowpack, the natural reservoir. With climate warming, adaptability of the high-elevation hydropower system in California is in question as a shift in runoff peak can have important effects on power generation and its economic value.

The Energy-Based Hydropower Optimization Model (EBHOM, after Madani and Lund 2008) was used to study the climate warming effects on the high-elevation hydropower system in California. EBHOM is a state-wide model which includes more than 150 hydropower plants in California. These plants are associated with the low-storage, high-head reservoirs used for hydropower generation only, and are not included in CALVIN.

The changes in hydroelectricity generation under three different climate warming scenarios (historical, warm-dry, and warm-only) were simulated for the 1984–1998 period to investigate the adaptability of California's high-elevation hydropower system to climate warming (Figure 8). The warm-dry and warm-only climate change scenarios reduce average revenue by 12% and 1%, respectively (Table 10). Overall, climate warming results in changes in monthly energy generation and spill distributions. Higher and lower monthly generations are expected in low-value and high-value months with climate warming. Annual energy spill increases under the warm-only scenario and decreases under the warm-dry scenario. The available storage and generation capacities can compensate for snowpack losses to some extent. Storage capacity expansion, and to some extent generation capacity expansion, result in increased revenues. However, these expansions might not be economically justified.

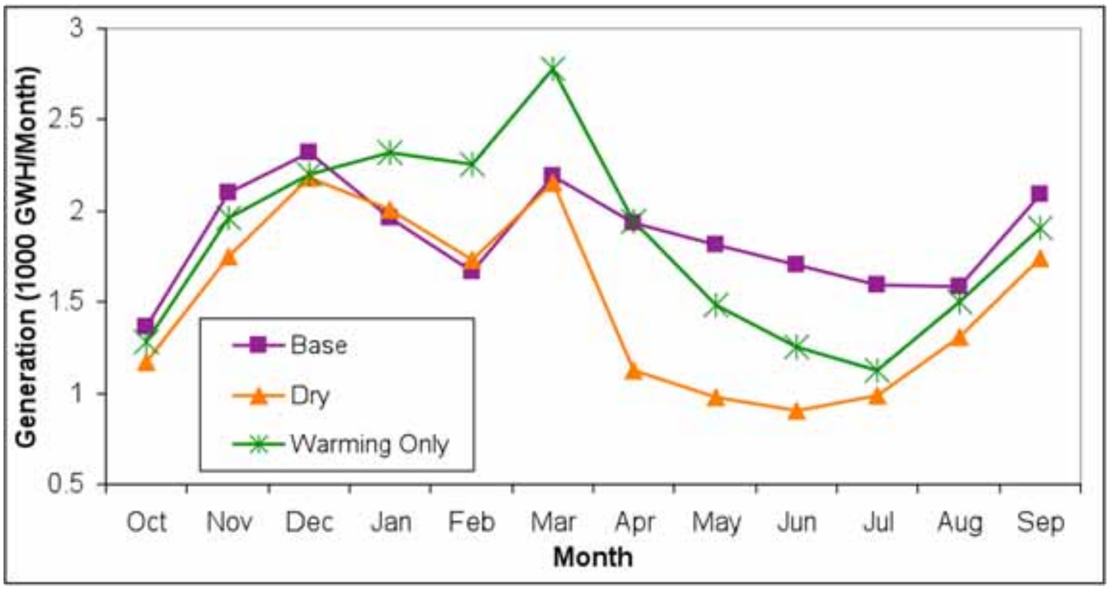


Figure 8. Average monthly high-elevation hydropower generation in California under different climate scenarios (1984–1998), after Madani and Lund (2008)

Table 10. Model results (average of results over 1984–1988 period) under three climate scenarios (after Madani and Lund 2008)

	Scenario		
	Base	*Warm-Dry*	*Warm-Only*
Generation (1000 GWh/yr)	22.3	18.0	22.0
Generation Change with Respect to the Base Case (%)		- 19.3	- 1.4
Spill (MWh/yr)	433	224	735
Spill Change with Respect to the Base Case (%)		- 46.0	+ 58.8
Revenue (Million 2008$/yr)	1,681	1,474	1,665
Revenue Change with Respect to the Base Case (%)		- 12.3	- 0.9

3.5. Model Limitations and Areas for Further Investigation

Limitations inherent to optimization models and CALVIN have been discussed extensively elsewhere (e.g., Jenkins et al. 2004). For this study in particular, there are two main caveats. The first one is related to the urban water use and scarcity cost, this is assumed constant for all three hydrologic scenarios. Evidence shows that a warm-dry hydrology may adversely affect yields for some crops in California (Adams et al. 2003; Lobell et al. 2007). Nevertheless, similar estimates are not available at the moment for urban water use. Thus, water demands for these three scenarios are rather a static projection towards year 2050; the bias introduced will depend on whether warmer climate increases per capita use, and whether this increment offsets or not reductions due to water conservation measures in the municipalities.

The second limitation of this study is related to the bias implicit in the estimated warm-only hydrology. Having a mean annual streamflow ratio between the historical and warm-dry scenario for the entire time span can impose a positive bias for flows in the winter runoff. This limitation can be addressed either by using mean annual streamflow ratios by year type or by using a downscaled simulation of hydrology that follows a warm-only pattern, when available.

For reservoir operations, some further investigations on cold-water operations for salmon and other species with a warmer climate and flood-specific operations would be useful additional studies.

4.0 Conclusions

Six major conclusions arise from this study.

1. Agriculture remains the most vulnerable user to water shortages for all climate scenarios. For non-dry scenarios, current agricultural uses are expected to shift to support population growth in California. Water shortages of more than 20% of the target agricultural water demands are expected with annual costs to agricultural production close to $870 million.
2. Water scarcity and its cost to California appear to be more sensitive to reductions in precipitation than to temperature increases. Temperature rise alone does not seem to increase water shortages significantly. This is in line with classical reservoir operation theory for a system with overyear water storage capacity (Hazen 1914).

3. Reservoir storage operations confirm previous findings and results of other studies, where reservoir levels in a warm climate peak earlier in the year respect to historical conditions. Storage levels are also unambiguously lower for the summer months.
4. A statewide increment in operating costs as high as 4.5% is expected under the warm-dry scenario. The warm-only climate scenario causes rather modest increments in these costs for both average and dry year types.
5. Revenue losses to low and high elevation hydropower are expected under both warm-dry and warm-only scenarios. Spills increase, but revenue losses are less than energy losses.
6. Average annual warm-dry rim inflows when generated by analysis using 18 basins and 6 basins, cause similar reductions in stream inflows from the historical hydrology. Increasing the level of detailed hydrologic representation in this system might not greatly affect overall estimates of climate warming effects and adaptations for California's water supply.

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6.0 Glossary

ac	acre
BCM	billion cubic meters
CALVIN	California Value Integrated Network, http//:cee.engr.ucdavis.edu/CALVIN
cm	centimeter
CVGSM	Central Valley Groundwater-Surface Water Model
CVPM	Central Valley Production Model
DWR	Department of Water Resources
EBHOM	Energy-Based Hydropower Optimization Model
GFDL CM2.1 A2	Geophysical Fluids Dynamic Laboratory Climate Model 2.1 high-emissions global climate model, warm-dry, high-level emissions scenario
L	liter
MAF	million acre-feet
MCM	million cubic meter
SWAP	Statewide Agricultural Production Model
TAF	thousand acre-feet
USBR	United States Bureau of Reclamation
USDA	United States Department of Agriculture